Implementation of Two High-Density XBT Lines With TSG and IMET Instrumentation in the Tropical Atlantic

A research proposal submitted to the NOAA Office of Global Programs from the Atlantic Oceanographic and Meteorological Laboratory and the Woods Hole Oceanographic Institution for Climate and Global Change Atlantic CLIVAR and COSTA Program Priorities.

Gustavo J. Goni, PI, Oceanographer, NOAA /AOML, 4301 Rickenbacker Csway, Miami, FL 33149, (305) 361-4339

Molly O'Neil Baringer, Co-PI, Oceanographer, NOAA/AOML, 4301 Rickenbacker Csway, Miami, FL 33149, (305) 361-4345

Silvia L. Garzoli, Director, Physical Oceanography Division, NOAA/AOML Miami, FL 33149, (305) 361-4338

Catherine M. Steward, Chief Financial Officer, NOAA /AOML Miami, FL 33149, (305) 361-4300

Kristina B. Katsaros, Director, NOAA/AOML Miami, FL 33149, (305) 361-4300

Implementation of Two High-Density XBT Lines With TSG and IMET Instrumentation in the Tropical Atlantic

Abstract

The key objective of this proposal is to improve the existing climate observing system in the tropical Atlantic. Based on recommendations from the Climate Observing System for the Tropical Atlantic (COSTA) Workshop (Miami, May 1999) it is proposed here to increase data collection on two-low density XBT VOS lines (AX-27 between Houston and Buenos Aires, and AX-08 between New York and Cape Town) running across key regions in the tropical Atlantic. Three type of instrumentation are proposed for each line:

1. **EXpendable BathyThermographs, XBTs.** High density XBT measurements will be performed between 18N and 18S along each line, four times a year.
2. **ThermoSalinoGraphs, TSGs.** Sea surface salinity will be measured continuously along both lines, approximately 15 times a year.
3. **Improved METeorolgical instrumentation, IMETs.** Meteorological parameters (barometric pressure, relative humidity, air temperature, precipitation, short wave radiation, wind speed and direction, and sea surface temperature) will be measured continuously using improved measurement systems along both lines, approximately 15 times a year.

Given the importance of the tropical Atlantic in climate variability, and the scarcity of observations in the tropical Atlantic to investigate mesoscale processes, data obtained from the measurements along these two lines will be critical to improve the climate forecast by extending the coverage of sea surface temperature, sea surface salinity and fluxes in the tropical Atlantic. The data obtained from the observations will be used to:

1. investigate the space-time evolution of the upper-ocean thermal structure,
2. infer the upper ocean mass and heat transports,
3. improve local understanding of the air-sea exchanges and drive the syntheses of regional and basin-scale flux fields in the Atlantic, and validate NWP surface flux fields,
4. interpret and synthetize observations obtained from other sources, such as satellites, moorings, hydrographic cruises, and models.

These measurements combined with remote sensing data and modeling efforts will greatly benefit climate studies in the tropical Atlantic by **complementing the current observing system by measuring long term spatial-temporal variability of mesoscale oceanic features and their impact on climate.**

1 Introduction

Climate fluctuations over the continental land masses surrounding the Atlantic Ocean have been documented since the 1940's. Multi-decadal swings in climate include changes in rainfall, temperature and even hurricane intensity and frequency. In particular the tropical Atlantic variability (TAV) appears to play a direct role in these coherent climate fluctuations. Modeling studies suggest that TAV is forced by air-sea interactions in the tropical Atlantic that may involve both thermodynamic and dynamical feedback. The first involves the interaction between the trade winds and sea surface temperature (SST) along the equatorial wave guide (Zebiak, 1993). The second involves the interaction between wind-induced surface heat flux and SST off the equator, contributing primarily to the variation in cross-equatorial SST gradients (Enfield and Mayer, 1997). The equatorial SST variability excited by zonal wind anomalies in the western equatorial Atlantic becomes an important influence on the larger tropical South Atlantic (Figure 1) region by producing a mode similar to ENSO . This phenomena can set off a sequence of events in the meridional direction that affect the meridional gradient of SST, the migrations of the ITCZ and climate in the region (Enfield *et al*, 1999).

These SST gradients are the key factor in driving the climate response in the tropical Atlantic and even over land areas as distant as the southern United States. A number of studies point to the dominance of SST fluctuations in the off-equatorial regions (± 5 to $\pm 15°$) as a determinant of the meridional gradient across the equator.

The surface heat balance, the nexus between temperature change and the forcing mechanisms, is critical for understanding what drives changes in SST. In particular, the terms primarily responsible for seasonal changes and associated anomalies and their geographical variability remain unknown. For instance, recent studies have shown that TAV and the North Atlantic Oscillation (NAO) fluctuate in phase with properties of water masses subducted from surface layers into the equatorial thermocline (Yang, 1999). Other studies of Rodwell *et al* (1999) have shown that TAV is linked to NAO variability and that TAV may be forced by the NAO as well as forcing NAO-like SST responses over large portions of the North Atlantic. Watanabe and Kimoto (1999) investigated the effect of the sea surface fluctuations in the tropical Atlantic on the North Atlantic atmosphere-ocean system using a general ocean-atmospheric coupled

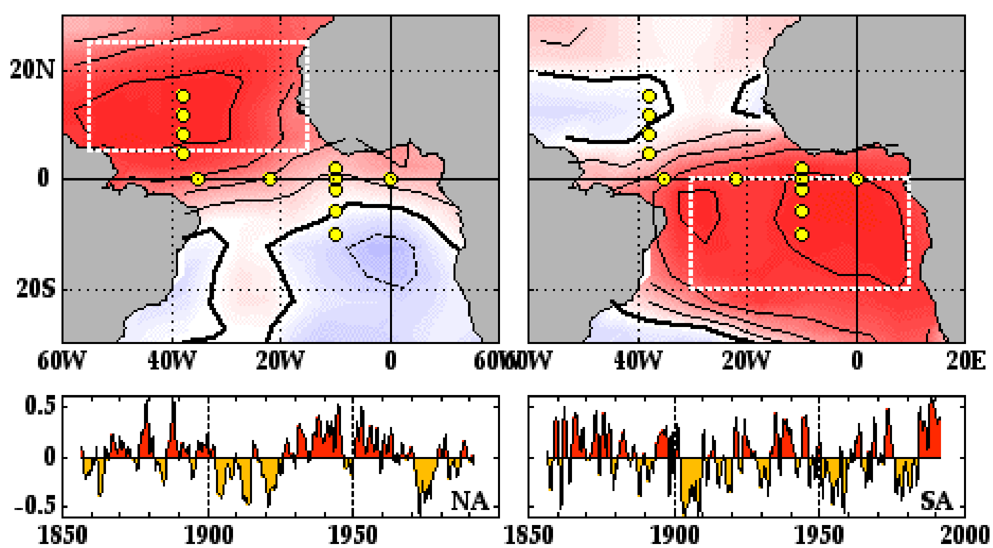

Figure 1: (top) Tropical Atlantic distributions of correlation between the gridded Kaplan *et al* (1998) sea surface temperature anomaly (SSTA) (smoothed, El Niño-Southern Oscillation and trends removed) and two rotated empirical orthogonal functions (EOFs) of the data with high explained variance in the (lef) North Atlantic and (right) South Atlantic. Positive values are in red and negative values are in blue. Dahsed rectangles denote the areas over which the tropical North and South Atlantic area indice of SSTA are calculated. The location of the PIRATA array are included in the figure.

model and concluded that the SST in the tropical Atlantic enhances the NAO, the leading mode in the North Atlantic. Therefore, it is critical to investigate the upper ocean heat content and the dynamics to understand the mechanisms that drive the fluctuations of SST anomalies.

One of the most important transport mechanisms in the Atlantic ocean is the Meridional Overturning Circulation (MOC) driven by temperature, salinity and by the wind variations. The transport of heat produced by the MOC on decadal and longer temporal scales is central to understanding climate variability. In the equatorial Atlantic, of most concern to the upper ocean heat balance is the cross-equatorial exchange of near surface waters that make up the upper limb of the MOC. Waters from the South Atlantic subtropical gyre cross through the equatorial circulation system to finally enter into the North Atlantic subtropical gyre. The wind driven patterns in the tropical Atlantic are complex and contribute to the three dimensional circulation, as in the case of the equatorial upwelling and off-equatorial downwelling. Southern hemisphere water makes its way into the north Atlantic through two primary pathways: rings shed by the North Brazil Current (NBC) as it retroflects into the interior, and seasonal rectification of the upper layer currents that allow warm surface waters to be stored in the North Equatorial Counter Current (NECC)/North Equatorial Current (NEC) Ridge system and released northward via Ekman transports (Mayer and Weisberg, 1993).

The main surface currents in the tropical Atlantic are the South Equatorial current (SEC), the Brazil (BC) and North Brazil (NBC) currents, the North Equatorial countercurrent (NECC), and the North Equatorial current (NEC) (Figure 2). The SEC flows to the west and branches into the NBC and BC between 20 and 5S. ADCP measurements show that the NBC transports approximately 23 Sv in the upper 300 m (Bourles *et al*, 1999). The NBC rings probably represent the largest contribution of South Atlantic waters into the North Atlantic basin (Fratantoni *et al*, 1995). However, the partitioning of the circulation pathways between the basin interior and the rings and its spatial and temporal variability remains a fundamental question. The study of the dynamics of the SEC, NBC, NECC and NEC is crucial to understand the inter-basin flow and variability.

Developing a better understanding of the role of air-sea interaction in maintaining persistent tropical Atlantic upper ocean thermal structure anomalies and of the impact of those anomalies on regional and global climate variability are central goals of CLIVAR in the Atlantic (e.g., COSTA, 1999). To achieve these goals it is critical to reduce the errors in present estimates of the air-sea exchanges of heat, freshwater, and momentum. Improving the *in-situ* observations of surface meteorology and the air-sea fluxes is an essential element of the strategy for developing accurate air-sea flux fields for the Atlantic. It has been recognized (Climate Observing System for the Tropical Atlantic, COSTA, 1999) that there is a need for the monitoring of the tropical Atlantic circulation to investigate the seasonal cycles of circulation and heat advection. The thermohaline circulation can be investigated by using Volunteer Observing Ship (VOS) XBTs and thermosalinographs (TSGs), PALACE floats, and the current Pilot Research Moored Array in the Tropical Atlantic (PIRATA) array. However, among them, only the VOS high density XBTs can provide sustained basin-wide measurements. of the upper ocean thermal field to investigate mesoscale variability. The surface wind-driven circulation can be investigated by VOS with accurate *in situ* wind fields.

Lines that are being simultaneously surveyed by high and low density VOS XBT are extremely beneficial. The low density observations provide an important context consisting of long-term climatologies and improved temporal resolution that balance the high spatial resolution of the high resolution sampling. Therefore, existing low density lines become the best candidates for new high density XBT sampling. High density XBT in VOS lines, produce closely spaced observations that resolve mesoscale spatial structures.

High density lines running across the equatorial Atlantic can also provide detailed information on the upper ocean (800 m) thermal structure and dynamics, which are critical for ocean-atmosphere climate studies.

As part of the COSTA and to complement the extended PIRATA array, the high density XBTs lines will provide high resolution observations in areas not covered by these moorings. Sustained measurements of high density XBT, sea surface salinity (SSS) and meteorological observations, used in conjunction with altimeter-derived sea height anomaly and scatterometer-derived wind data will provide critical information to investigate the interaction between the atmosphere and ocean, and its impact in the regional and global

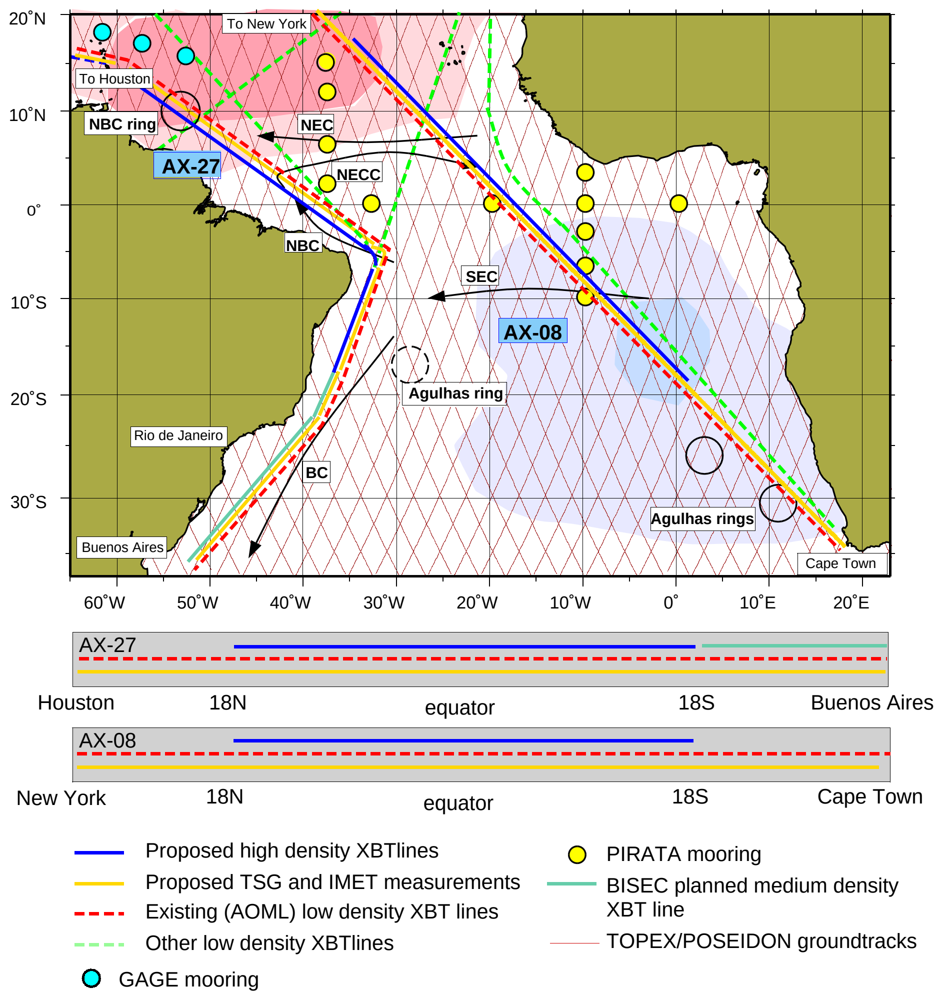

Figure 2: Approximate schematic distribution of surface currents in the Tropical Atlantic. The South Equatorial current (SEC) bifurcates into the (SW flowing) Brazil current (BC) and the (NW flowing) North Brazil current (NBC). The NBC retroflects to shed warm anticyclonic rings and to form the North Equatorial Counter current (NECC). The North Equatorial current (NEC) flows westwards to also contribute to the formation of anticyclonic rings. The proposed high density XBT lines (AX-27 and AX-08) are indicated in solid blue. The dotted red lines indicate existing AOML low density XBT lines, dotted green lines indicate other low density observations being carried by VOS. The green solid line indicates the proposed section of AX-27 supported by BISEC. The yellow circles show the locations of the PIRATA moorings. The tropical Atlantic distributions of correlation between the gridded SSTA and two rotated empirical functions are also shown in the background, with reds are positive and blue are negative values (adapted from Enfield *et al*, 1999). The TOPEX/POSEIDON altimeter groundtracks are superimposed to the figure.

climate responses, and to understand the dynamics of the upper ocean in the tropical Atlantic, which cannot be obtained from other existing observing systems.

These high density lines surveyed over extended periods (longer than four years) will allow to estimate mean eddy geostrophic transports by combining altimeter with XBT data, and Ekman transports which can be used for calibration of ECMWF wind fields. In particular, high density XBT lines with coincident high quality air-sea fluxes, are extremely useful for:

- providing extended coverage of SST, SSS and fluxes to improve climate forecast,
- investigating the role of air-sea interaction in the evolution of SST and upper ocean structure in the Atlantic

What is unique about these two VOS lines?

The XBT information provided along lines AX-27 and AX-08 is critical to understanding the mesoscale dynamics in the tropical Atlantic. The observations gathered along these lines will complement and greatly enhanced those collected by the PIRATA moorings and hydrographic cruises. In fact, they represent the only means to investigate the temporal and spatial variability of the upper ocean dynamics and of mesoscale features such as warm rings.

The high density XBT observations are proposed in the two lines between approximately 18N and 18S. The separation between consecutive XBT drops will be 40 km, although a finer spatial resolution of 20 km will be used depending on mesoscale features being detected. A total of approximately 150 XBTs will be launched between 18N and 18S in each line in each cruise. These lines will be repeated four times a year, going from Houston to Buenos Aires (AX-27) and from Cape Town to New York (AX-08). These two lines are currently being sampled sporadically, due to ship commitment constraints, with low density XBTs.

The two VOS lines cross the Tropical Atlantic in regions with large mesoscale variability (Figure 3a): The northern section of line AX-27 crosses a region dominated by the presence of warm anticyclonic rings. Although these rings are mostly originated at the North Brazil current retroflection some of them are originated by the North Equatorial current. Although altimetry is very useful for detecting warm anticyclonic features a subsurface ring (Ring C in figure 3d), undetected from sea height anomaly data, was observed during the first North Brazil Current Ring Experiment cruise in November and December 1998. This ring had almost negligible velocity at the surface, velocities of up to 2 ms^{-1} at 150 m deep, and no positive sea surface height anomaly signature. This case highlights the importance of repeated hydrographic measurements in the region for investigating the transport of warm anticyclonic rings, as altimetry does not detect some of these subsurface features. Preliminary studies (Goni and Johns, 2000) show that the four to seven rings observed every year by altimeter data remain in the region approximately three to four months. A map of TOPEX/POSEIDON-derived sea height anomaly data during mid December 1998 (Figure 3b) reveals the existence of two anticyclonic rings in the region. The solid blue line in the same figure shows the approximate location of line AX-27, while the dotted white line indicates the T/P groundtrack d311. Statistics of the warm anticyclonic rings detected by T/P from October 1992 until November 1998 show that line AX-27 approximately follows their mean trajectories (Figure 3d). Given the characteristics of the dynamics in this region, a high density XBT line repeated four times a year will capture the hydrograpy all anticyclonic rings in the region.

The central region of line AX-27 crosses the North Brazil current retroflection. Previous studies show that this region is characterized by large temporal and spatial variability. High density spatial reso-

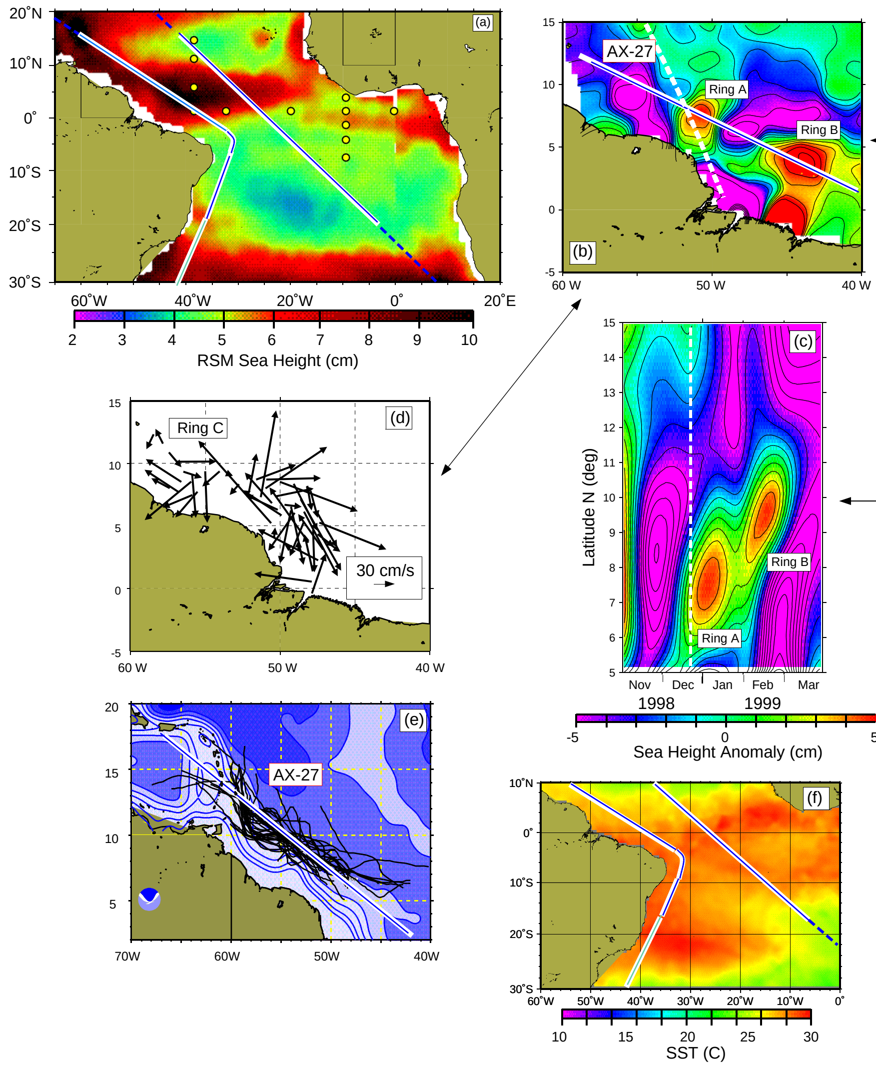

Figure 3: Dynamics and mesoscale features in the region of study.(a) TOPEX/POSEIDON (T/P)-derived rms sea height variability in the Tropical and South Atlantic. (b) T/P-derived sea height anomaly for mid December 1998. The regions of higher sea height anomaly values are associated to a warm anticyclonic (Ring A) ring and with the retroflection. The blue line indicates AX-27 and the white dotted line is the T/P descending groundtrack d311. (c) Space-time diagram for the selected T/P groundtrack of Figure 3b. The white dotted line indicates the time when the snapshot shown in Figure 3b was taken. Ring A is shown in the figure. Ring B, pinched off at the retroflection by the end of December crossed groundtrack d311 during February 1999. (d) ADCP-derived velocity vector field during mid December 1998 obtained during the first NBC Experiment project cruise. Two anticyclonic rings are present, one of which (Ring C) was virtually undetected by altimetry. (e) T/P-derived anticyclonic ring trajectories between November 1993 and December 1998. AX-08 (blue line) is superimposed. The bathymetry is also included for reference. (f) AVHRR-derived sea surface temperature composite for the period February 24-28, 1995, showing warm regions associated with the SEC and NECC, and SEC bifurcation. Lines AX-27 and AX-08 are included in the figure.

lution XBT observations will be critical to the investigation of the spatial and temporal variability of the retroflection when combined with altimetric data. The conclusions derived by the XBT observations here will be greatly enhanced by the profiles derived from three nearby PIRATA moorings. The southern region of line AX-27 crosses a region where the South Equatorial current bifurcates into the NBC and BC. The vertical structure of this region, as well as its temporal and spatial variability are largely unknown. The high density XBT observations are needed to properly identify the location of this bifurcation and quantify the mass transport carried by each of these currents. South of 18S, this line would be partly supported by BISEC to provide a better understanding of the BC transport.

Line AX-08 crosses the Equator in the tropical Atlantic at around 20W, splitting the region in two. The information provided by the XBTs, TSGs and IMETs in this line is critical to the investigation of the upper ocean dynamics in this region, including the flow of the South Equatorial current, North Equatorial counter current and the North Equatorial current. The large spatial sea height variability exhibited by the NEC and NECC (Figure 3a) makes the combination of altimeter-derived data and XBT temperature profiles an excellent tool to help investigate the dynamics of upper ocean thermal structure. The low variability of sea height found south of the equator underscores the importance of investigating the mesoscale dynamics using high density XBT measurements. The strategic path of this line serves to fill the gaps existing in the PIRATA moorings and other related (funded and proposed) projects.

2 Project Objectives

The data to be collected will:

1. extend the coverage of SST, SSS, and fluxes in a region critical for climate and weather forecast, and
2. provide a valuable data set to study the dynamics of the upper tropical Atlantic and its relation with climate.

It will be analyzed in conjunction with the ensemble of data from observations obtained in related projects (see Section 6), including the PIRATA array and COSTA components, with the following objectives:

- to investigate the role of air-sea interaction in the evolution of SST and upper ocean thermal structure,
- to maintain a database in real-time with the fields obtained from the XBTs, TSGs and IMETs, and distribute its contents to the scientific community, and to maintain the processed data in a NOAA/AOML web page with approximately one week delay,
- to infer the upper ocean eddy transports and heat fluxes using the data obtained from the measurements,
- to investigate the interannual fluctuations in the geostrophic and Ekman transports, heat and freshwater across the tropical and subtropical boundaries,
- to compare results obtained from the XBTs, TSGs and IMETs with observations obtained from other sources, such as satellites, moorings, and to model results (mixed layer PWP model and NCEP coupled model project),

- to improve satellite observations by merging altimetry with upper ocean hydrographic data, and by comparing satellite (e.g. QuikSCAT) with *in-situ* observations,
- to compare results against available climatologies (Reynolds and Smith, 1994; Woodruff *et al*, 1987; Servain *et al*, 1996; Oberhuber, 1998; and da Silva *et al*, 1994,
- to compute dynamic height fields with blended TOPEX/JASON-1 and ERS-2 sea height anomaly data as in Goni *et al* (1997),
- to support a pilot program at NOAA/AOML to investigate the effect of the upper ocean thermal structure in hurricane intensification (Shay, Goni and Black, 2000) in support of the NOAA/NSF USWRP program on Tropical Cylones (Shay and Goni, PI's),

3 Methodology

This project consists of augmenting two VOS XBT lines to include high density sampling of XBTs (with average XBT spacing of about 40 km and each section occupied 4 times per year). The line AX-27 cuts through the western tropical Atlantic where the North Brazil Current retroflects and sheds eddies, while the line AX-08 crosses the center of the tropical Atlantic across the major current systems in the region including the NEC, NECC, and the SEC. Both of these lines are currently maintained by NOAA/AOML with low density XBT observations (typically 1 XBT per 300 km every time the line is surveyed) with ships traveling along each line between eight to twelve times a year, depending on availability.

Under this effort, two key new additions to the more typical high-density VOS XBT-only *in-situ* observing system is proposed: the installation of IMET (Improved METeorological) modules, for the collection of accurate surface meteorology and air-sea fluxes on two long, basin-scale lines that transit the western tropical Atlantic and the installation of TSG instrumentation, for the collection of surface salinity and temperature. IMET and TSG data will be recorded on board once per minute, and the averaged data will be telemetered along with the XBT data.

The XBT measurements will provide vertical profiles of temperature up to 800 m deep between 18N and 18S four times a year in each line. The TSGs will provide sea surface temperature and salinity observations between end ports (Houston-Buenos Aires and Cape Town-New York) approximately 15 times a year in each line. The IMET instrumentation will collect measurements of wind speed and direction, barometric pressure, incoming SW and LW radiation, precipitation, relative humidity and air temperature, along both lines between ports approximately 15 times a year.

This work proposes to use TSG-derived surface salinity to statistically infer the vertical salinity profile using the XBT-derived vertical thermal profile and climatology based on a methodology proposed by Hansen and Thacker (1999). The XBT high density drops will be limited to the equatorial and tropical band. As the observing system in the tropical Atlantic evolves, profiling Argo floats will provide broad scale sampling of upper ocean temperature and salinity. Proposed here is low density sampling using XCTDs four times per section that together with ARGO will provide the climatology for subsurface T/S correlations. Thus, the focus of the proposed work is on the unique information that the high density XBT sampling, continuous surface salinity and high quality meteorological sampling will provide and the unique contribution that sampling in the tropical Atlantic would make. However, the need for air-sea flux and surface salinity data across the whole Atlantic basin is pressing and a unique contribution of the VOS IMET and TSG sampling is the large scale sampling as well as in the tropics.

The temperature and salinity fields can be used in combination with altimeter-derived sea height anomaly data as, in general, sea surface heights are correlated with changes in the depth of the thermocline and with the steric changes integrated over the water column. The combination of sea height anomalies with temperature fields have been shown to be very successful in interpreting upper ocean dynamics (Kelly, 1996; Goni *et al*, 1996). In particular, high density XBT profiles have been successfully used in combination with altimetry to investigate steric variability and upper ocean dynamics (Gilson *et al*, 1999). Detailed measurements of the temperature and salinity fields will enhance the use of altimeter data over the whole region. The effect of salinity on the dynamic height in the western tropical Atlantic is also important as this region is affected by heavy rainfall and the outflow of the Amazon river. Recent studies that combined the use of altimetry and hydrographic data have shown that low salinity waters from the Amazon river can be found as far as in the Lesser Antilles and the Caribbean Sea (Kelly *et al*, 2000).

Data Management

The vertical temperature profiles, the surface salinity and the time-averaged IMET-derived meteorological parameters will be obtained in real-time through the GTS system. This raw data will be available to the scientific community upon request. Processed data will be also available with one week delay through a web page, probably with the already existing high density XBT data of lines AX-07 and AX-10. Past and real time low density XBT data of lines AX-08 and AX-27 will be also included in the web page. Every effort is made to also include data from the other low density lines in the region to create one web page with a comprehensive data set of XBT data in the tropical Atlantic.

XBT- and TSG-derived data will go through the same intensive quality control that the low density data is given at NOAA/AOML GOOS Center. IMET data will receive quality control at WHOI, be integrated with the XBT and TSG data, be provided to the FSU COAPS flux archive, and made freely available. The data will be also distributed to other users, for instance to the NOAA/Hurricane Research Division to help investigate the relationship between hurricane heat potential (a measure of the integrated vertical temperature) and the intensification of hurricanes.

This data will enhance the vastly poor hydrographic observations available in the regions crossed by the two high density lines. Low density XBTs, TSG-derived and IMET-derived observations will be available approximately 15 times a year along each of the lines. High density XBT observations will be available 4 times a year along each line.

The data will be merged with altimeter-derived sea height anomaly data and scatterometer (QuikSCAT)-derived wind fields produced at AOML/IFREMER, to investigate the upper ocean circulation in the tropical Atlantic. IMET-derived observations and heat flux derivations will be compared from those obtained daily from the AOML/IFREMER, from NWP models and from remote sensing. They will also be made available in real near real time to modeling, remote sensing, and assimilation groups. Raw, one-minute data will be recovered from the IMET systems during servicing calls ($\approx$ 6 months) to the ships, quality controlled, and also made available.

XBT Observations on the VOS Lines

The vertical profiles of temperature obtained from the high density observations will be used to investigate the temporal and spatial variability of the upper ocean thermal field in the tropical Atlantic. These profiles will be combined with surface salinity observations and climatology to infer the vertical salinity profile. These XBT/TSG-derived salinity profiles will be compared against actual salinity profiles obtained from XCTDs dropped in every XBT high density cruise. The XBT temperature profiles, along with the data obtained from the TSGs and IMETs will be crucial to investigate the geostropic and Ekman transports. The mass transports will be used to estimate the partitioning of the flow across the equator between the NBC and the interior flow. The temperature profiles will be also critical in the study of the NBC rings and in the investigation of the bifurcation of the SEC.

Thermosalinograph Observations on the VOS Lines

The themosalinograph (TSG) will be operational every time the VOS ship carrying the instrument is out of port. It is estimated that the two lines will be sampled approximately 15 times a year. The TSG-derived sea surface salinity will be used to estimate the actual salinity profile using a methodology developed by Hansen and Thacker (1999). This methodology demonstrated that the vertical salinity profile can be estimated from regressions against the thermal profile and can be greatly improved if combined with the value of the surface salinity and latitude (Figures 4a and 4b). These profiles will be combined with the XBT-derived temperature profiles between 18N and 18S to compute the dynamic height (off the equator), study the dynamics in the region and investigate the relationship between the upper ocean thermal/saline structure and altimeter-derived sea height. The sea height, dynamic height and wind fields will be used to estimate the water transport of the mayor surface warm currents and to investigate the across the equator mass flow. XCTDs deployed four times per crossing coupled with the coarse resolution Palace float (ARGO) salinity profiles will help define the climatology of subsurface temperature and salinity correlations used in this analysis.

IMET Observations on the VOS Lines

The installation of the IMET modules has two purposes in this project:

1) To improve the local understanding of the air-sea exchanges along these VOS lines. Taken together with the high density XBT and TSG sampling, the knowledge of the surface forcing will be used to examine the role of local air-sea interaction in the evolution of the upper ocean temperature and

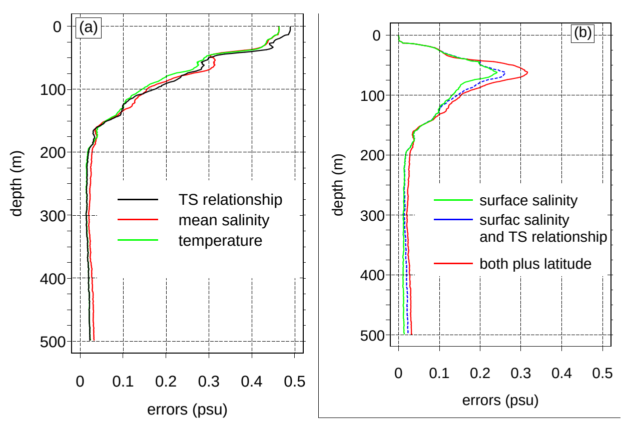

Figure 4: Root-mean-square errors for various methods of estimating the salinity profiles. (a) Errors for the TS relationship, mean salinity profile, and regression on temperature, (b) Errors for regression on surface salinity and temperature, and surface salinity, temperature and latitude. (*Adapted from Hansen and Thacker, 1999*)

salinity fields along the ships track. The IMET modules will measure wind speed and direction, air and sea surface temperature, barometric pressure, incoming shortwave and incoming longwave radiation, and precipitation and thus will provide complete and accurate local records of surface meteorology and of the fluxes. These records will be used to develop corrections to the surface forcing time series available very 6 hours from numerical weather prediction models (ECMWF and NCEP) and from satellites (radiation and precipitation, in particular) at points along the ships' tracks. These corrected time series will in turn be used to quantify, by using one-dimensional ocean models and by checking the closure of one-dimensional upper ocean heat and freshwater budgets, the extent to which the evolution of the observed upper ocean structure along these tracks is driven by local air-sea exchanges. The corrected winds will also provide a better estimate of the Ekman contribution to the heat transport across these lines (Roemmich *et al.*, 2000).

2) To drive the syntheses of regional and basin-scale flux fields in the Atlantic. This will be done by providing high quality surface fluxes on long lines that span areas of critical scientific interest, that are in some places data sparse, and in some places will be in close proximity to other *in-situ* platforms. The high quality *in-situ* data will identify errors in other data sets, motivate joint efforts to improve Numerical Weather Prediction (NWP) models and satellite products, provide the means to develop corrections to these products, and guide the preparation of synthesized flux fields for the Atlantic.

The development of the methodology for developing global surface flux products by synthesizing *in-situ* observations, NWP fields, and remote sensing products is the focus of a companion proposal (Yu and Weller). This effort will use the Atlantic as a pilot study to test techniques to be used later for the global fields. Briefly, higher spatial and temporal resolution and more uniform, consistent coverage of the Atlantic is sought than can be achieved from *in-situ* data alone. The coverage limitations of flux fields derived from *in-situ* data alone are evident when such fields are compared with those from an NWP reanalysis (White and da Silva, 1999). The 6-hourly time resolution, global coverage, and dynamic framework for assimilation of *in-situ* data provided by the NWP models make NWP fields attractive alternates, as does the global coverage provided by satellites. However, development of present NWP models has been driven by the desire for better forecast skill and not with attention to the quality of the fluxes they produce. Satellites can provide SST, wind, surface shortwave radiation, precipitation, and, possibly, surface longwave radiation, wind stress, sensible and latent heat flux. Unfortunately, because of the coverage characteristics of the satellites (swath width, number of satellites, orbit), global coverage is not achieved that resolves the diurnal cycle and, in some cases, the passage of synoptic weather events. Thus, a successful strategy will be based on techniques that combine *in-situ*, NWP, and remotely-sensed fields. In this strategy, the *in-situ* observations are essential to identify and correct errors (biases and those with space and time variability) in the NWP and remotely-sensed fields and to provide high temporal resolution at select points together with high spatial and temporal resolution along select lines. They are also essential as the *in-situ* observing community's contribution to developing partnerships with the NWP, remote sensing, and ocean modeling and data assimilation communities that will be working in the Atlantic.

Both high quality fixed points and the VOS lines are seen as essential elements. Weller *et al* (1999) used *in-situ* data from a widely-spaced array of five surface moorings in the northeastern Atlantic together the fields from NCEP and ECMWF to produce hourly fluxes on a 1 degree grid between 10 and 40N and 10 and 40E. However, such a procedure assumes that the errors in the NWP fields have large space and time scales. To what extent this is true is presently unknown. In our proposed effort, the IMET-equipped VOS will be used to characterize the spatial structure of the surface meteorological and flux fields, to check the spatial structure of the error fields (NWP vs *in-situ*, satellite vs *in-situ*, synthesized vs *in-situ*), and, taken together with the fixed point time series, to examine the space/time decorrelation of the surface meteorological and air-sea flux fields. It can be anticipated, for example, that AX-08 will, when crossing the equatorial Atlantic, see reductions in incoming shortwave associated with Saharan dust and point to errors in the NWP and satellite radiation fields.

The *in-situ* observing platforms include an IMET-equipped surface mooring to be located beginning in late 2000 at 15N, 51W (proposed by A. Plueddemann). AX-08 passes to the north of this site at 300-500 km closest separation and AX-27 passes to the south of this site at 500 km closest separation. AX-27 also passes close to the western end of the PIRATA array, while AX-08 cuts diagonally through that array as it crosses the equator. In addition, AX-08 and AX-27 are embedded in the existing network of Atlantic VOS that make the routine meteorological reports that form the basis of the COADS (da Silva et al., 1994) data set. The buoy at 15N, 51W would have the same sampling as the IMET-equipped VOS (SST, air temperature, wind speed and direction, relative humidity, incoming shortwave, incoming longwave, barometric pressure, and precipitation sampled every minute). The Atlas buoys in the PIRATA array have wind speed and direction, air and sea surface temperature, relative humidity, incoming shortwave radiation, and precipitation sampled less frequently to save power. The standard VOS have barometers, sea surface temperature sensors, wet and dry bulb thermometers, and anemometers and also make visual observations of cloud cover and precipitation. The IMET VOS and buoy rely on the bulk formulae for sensible and latent heat flux and for the wind stress, on using the surface albedo to determine net shortwave radiation, and on an approximation of the sea surface as a black body to get net longwave radiation. Deployments of such well-instrumented buoys coincidentally with ships equipped to measure the fluxes with attended sensors (including those needed to make eddy covariance flux measurements) have shown that mean fluxes ($\approx$ 3-week average) from such buoys are accurate to better than 10 W m^{-2} (Weller and Anderson, 1996). Additional empirical formulae are needed to determine the fluxes at the PIRATA buoys.

The IMET data from the VOS and buoy will be compared at various space and time lags to examine the space/time character of the surface meteorological and flux fields. Comparisons with the PIRATA buoys and routine VOS reports will be done not only to look at the structure of the fields but to also to compare the data they recover with their respective different methods and sampling strategies. An extensive laboratory and land-based field comparison of the IMET and ATLAS buoy meteorological systems will be carried in the summer of 2000 at WHOI and aid in interpreting the data from the Atlantic comparisons. Historically, the means to collect and map the fluxes has been to use the surface meteorology from the VOS together with empirical formulae. Early use of the VOS data encountered data quality problems, especially due to different methods of obtaining SST, to disturbance of the airflow by the ship itself, and to errors in calculating the absolute wind velocity (Folland and Parker, 1995; Kent *et al.*, 1993a; Taylor *et al.*, 1999a). More recently, as in the preparation of the SOC version of the VOS-derived flux fields, corrections (Kent and Taylor, 1995; 1996; 1997; Kent *et al.*, 1993b; 1998; Taylor *et al.* 1995; 1999a; Taylor and Kent, 1999) to these errors have improved the quality of the VOS-based fluxes. The success of these improvements is evident in the good agreement between the SOC VOS-based net heat flux and net heat fluxes observed on IMET-equipped buoys in the Atlantic in 1991-1993 (Subduction experiment) and in the Arabian Sea in 1994-1995 (Moyer and Weller, 1994; Josey *et al.*, 1999). Still, these VOS lack radiometers, and we believe that the IMET-equipped VOS data can be used to drive further improvements to the VOS-based flux fields and to fields that assimilate the IMET-equipped VOS data. The PI's will work together with Peter Taylor's group at SOC on this. Our target is to obtain fluxes for the Atlantic where the net heat flux is specified to better than 10 $Wm^{-}2$. The PI's believe that present uncertainties, coming particularly from the radiative components and from the latent heat flux, are large. Therefore, this work proposes the IMET installation on AX-08 and AX-27 as an essential step toward reducing these uncertainties and making significant progress toward that target.

4 Instrumentation

4.1 EXpendable Bathythermograph, XBT, and AOML Autolauncher System

The XBT Autolauncher system was designed and built at AOML (Bitterman, 1995) and has been used in numerous oceanographic applications since 1995. The autolauncher system consists of the launcher and an associated computer system which controls all the launcher functions and logs the data. A GPS receiver is interfaced to the computer and provides navigation information. In addition, a Geostationary Environmental Satellite (GOES) system transmitter is used to transmit the data to shore in real time for distribution over the Global Telecommunications System (GTS). The launcher is mounted to the ship's rail near the stern. It has six launch tubes that are preloaded with XBTs that can be launched at programmable locations as the ship steams along its course. The depth of the temperature measurement is inferred from the XBT fall rate and the elapsed time of the measurement after it hits the water.

The launcher is connected to a personal computer. The AOML software which controls the autolauncher, can be set to launch the XBTs at programmable time intervals, at fixed latitude or longitude intervals, or at preset latitude or longitude positions. Precise time and location information are obtained from a GPS receiver. During the deployments, the data are displayed in real time to the operator, and a series of quality control checks are automatically made on each launch. The transmitted data stream is identical to that transmitted by all the other ships in the NOAA VOS program, so the data are then available to investigators world wide via the GTS distributions system.

To date, the AOML autolauncher system has been used on numerous high density XBT transits with very few failures attributable to the system itself. Failures that have occurred have been generally attributable to faulty XBTs or fouling of the wires from the XBT. In all cases the operator is notified by the software and corrective actions have been taken so that there have been no significant data losses on any of the transits.

4.2 Thermosalinograph, TSG

Based on the results of the intercomparison test the Seabird Electronics SBE 21 TSG was selected for installation on all of the ships. It contains a 3 electrode contact sensor for measuring the conductivity and a thermistor for the seawater temperature. Depending on the installation, a second temperature sensor is sometimes installed at the sea water inlet to obtain accurate ocean surface temperatures. The TSG has a two way computer communications interface so that sample rate and other setup information can be sent to the TSG and data can be received by the computer. In addition, a GPS receiver is installed and interfaced to the computer to provide accurate time and position information. Data are transmitted to shore in real time using either a Geostationary Environmental Satellite (GOES) system transmitter, or via a Standard C transmitter. This has proven invaluable in quality controlling the data, since the performance of the system can be monitored from AOML without any demands on the ship's crew. Software was written at AOML to control the operation of the system and has proven to work reliably on most ships.

In addition to the initial installation of the systems, it is imperative that samples be drawn on a regular basis to calibrate the salinities. As the systems inevitably foul due to biological growth, they must be removed periodically for refurbishment and recalibration. This work will include the installation and operation of these systems for a period of one year.

4.3 Improved Meteorology Instrumentation, IMET

Recently, the IMET technology has evolved into new modules designed for use on VOS ships. These new VOS-IMET are self-powered, self recording, stand alone units that also are able to communicate on the IMET Addressable-Digital-Data-Bus (ADDB). These units are being used on VOS in cooperation with the SIO-VOS Group as part of a NOAA - OGP program. Currently installed sensor modules include the full flux suite including: Wind Speed and Direction, Relative Humidity and Air Temperature, Barometric Pressure, Precipitation, Shortwave Radiation, Longwave Radiation, and Sea Surface Temperature. These modules are housed in Grade 2 titanium, which provides economical, corrosion-free, rugged units. Mounting is accomplished by fiberglass channel and stainless steel latches that provides easy installation in a wide variety of ship configurations. The target platform for these systems are large commercial ships that make voluntary observations.

One feature of the US VOS is that they are sold and change routes on a very regular basis. This has severe implications in that it is not feasible to run power and data cables whose installation to meet Coast Guard specifications would be time consuming and expensive. One special problem is getting sea-surface temperature data from inside the hull of the ship at the waterline up to the rest of the modules. An acoustic modem has just been developed that uses the ships steel hull at the acoustic path for 20-baud data. The measurement system for a VOS therefore must be self-powered, self-recording and able to communicate data to the bridge area for both ship use and satellite transmission. This means that the VOS climate observing system uses essentially the same sef-powered, internally recording components as a buoy climate observing system. Complete information on each of the IMET modules can be found in:

http : //kuvasz.whoi.edu/uop/asimet/asimet.html.

5 Work Schedule

NOAA/AOML has already identified and contacted many volunteer merchant ships from Americana Ships (Tampa, Florida) that have agreed to carry the instrumentation and technical personnel on board to maintain these two lines.

Year 1: Building and installing two XBT autolaunchers, and two TSGs. Building two IMETs. Calibrations. Four high density XBT cruises in each line, approximately 15 TSG cruises in each line. Distribution of data. Set up of web pages. Start to develop algorithms to infer salinity profiles.

Year 2: Building one spare XBT autolaunchers, one spare TSG and the spare IMET, which is used when the original instruments are being calibrated. Calibrations. Four high density XBT cruises in each line, approximately 15 TSG and 7 IMET cruises in each line. The IMET starts running by the mid part of the second year. Distribution of data. Data interpretation. develop algorithms to infer salinity profiles and publish results. Altimetry/XBT/TSG data fusion and computation of geostrophic and Ekman transports.

Year 3: Calibration of instruments. Four high density XBT cruises in each line, and approximately 15 TSG and IMET cruises in each line. Distribution of data. Data interpretation and publication of results. Comparison of IMET data with other sources of observations. Altimetry/XBT/TSG/IMET data fusion and computation of mass transports and fluxes.

Year 4: Calibration of instruments. Four cruises in each line. Distribution of data. Data interpretation and publication of results. Computation of mass transports and fluxes. Publication of results.

Estimates of partitioning of mass transports across the equator. Estimates of partitioning of mass transports of the SEC into NBC and BC. Publication of results.

Year 5: Calibration of instruments. Four cruises in each line. Distribution of data. Data interpretation and publication of results. Computation of mass transports and fluxes. Publication of results.

Readiness

High and low density XBT lines are being maintained in different regions by NOAA/AOML (Figure 5). It is evident that the Atlantic ocean is well undersampled by sustained XBT observations. The Two high density XBT lines, in the North Atlantic, AX-07 and AX-10, were implemented to monitor the heat flux variability (AX-07) and to investigate regions where temperature anomalies could have the greatest interaction with the atmosphere (AX-10).

AOML has also been installing and maintaining TSG observations along several shipping routes (Figure 5) since April 1996. XBT and TSG data is publically available in real time over GOES and GTS satellites. Quality controlled data, meta data and documentation is available through AOML's web sites at:
http://www.aoml.noaa.gov/phod/hdenxbt/ and
http://www.aoml.noaa.gov/phod/goos/tsgplot_list.htm.

WHOI's Upper Ocean Processes Group has been involved in measuring atmospheric fluxes, winds and studying the upper ocean dynamics since the early 1980's. Projects they have been involved in include PACS in the central Pacific Ocean, and Fasinex, Lotus and the Subduction Experiments in the North Atlantic Ocean. WHOI's group is well trained and well versed in all the intricacies of IMET instrumentation, while AOML is well versed at operational constraints and real time data transmission. Together, we expect an extremely successful collaboration.

6 Relevance to Other Programs

The work proposed here supports the objectives of COSTA and NOAA CLIVAR Atlantic to investigate and predict seasonal to decadal climate variability in the Atlantic ocean. Additionally, this work comple-

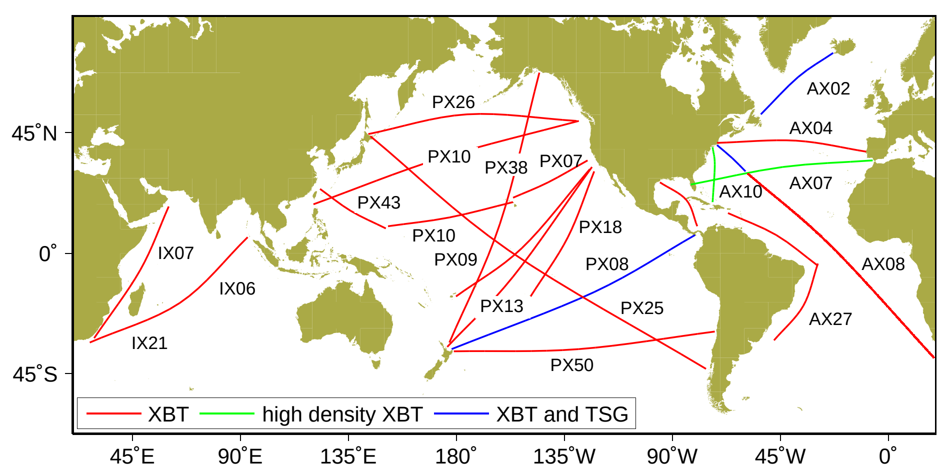

Figure 5: XBT lines maintained by NOAA/AOML.

ments and greatly enhances present and proposed observational programs in the Tropical Atlantic, such as:

A) Operational

1) low density XBT lines maintained by the US, France and the UK (present),
2) satellite-tracked drifting buoy data collected by different countries through various international programs (present),
3) the PIRATA array, maintained by the US, France and Brazil (present)
4) AX-07 and AX-10 high density XBT lines, maintained by NOAA/AOML (present),
5) the Array for Real-time Geostrophic Oceanography (ARGO) supported by the U.S. (proposed),
6) CORIOLIS, a French program that proposes to continue and improve the existing observing system (proposed);
7) Florida Current, a NOAA/AOML project to measure the Florida current using telephone lines (proposed).

B) Process Studies:

1) Atlantic Circulation and Climate Experiment (ACCE), a cooperative study between NOAA/AOML and WHOI to deploy PALACE floats (present),

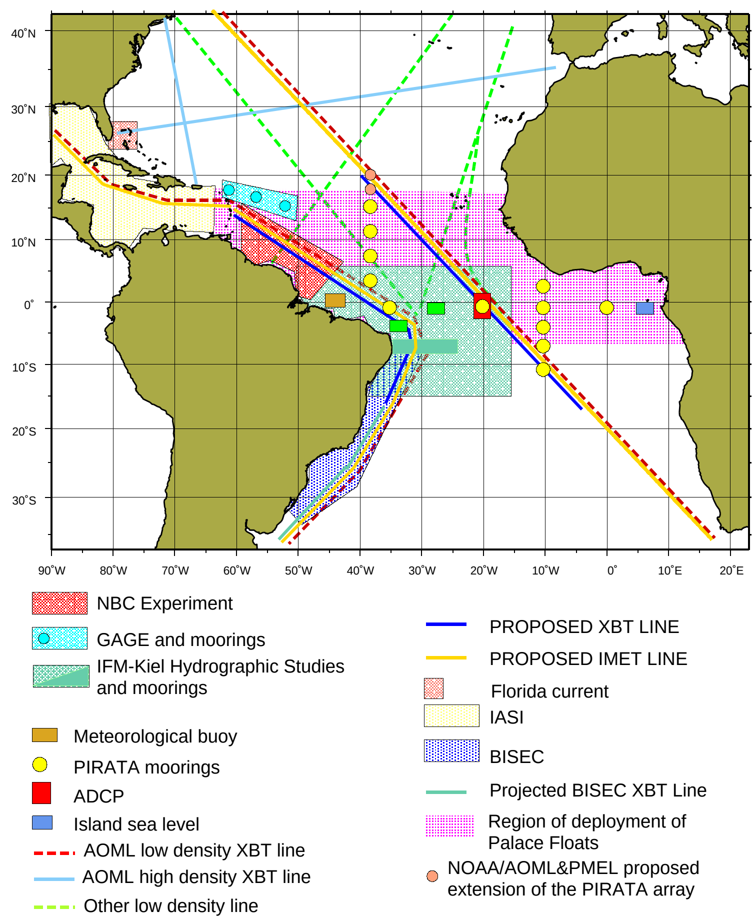

Figure 6: Summary of some of the present and proposed studies in the tropical Atlantic.

2) NBC Ring Experiment, a multi-institutional effort between the University of Miami, NOAA/AOML and Columbia University to carry out a comprehensive observational study of the North Brazil current retroflection and the the ring generation process (present),
3) RECONOB, a numerical study of the North Brazil current retroflection funded by the US and Brazil (present),
4) ECLAT, the French component of the international CLIVAR (present),
5) Guyana Abyssal Gyre Experiment (GAGE), a joint program between WHOI and IFM (Kiel, Germany) to investigate the Guiana Abyssal Gyre and its role in the MOC (present),
6) IFM-Kiel Programs in the tropical and subtropical Atlantic (present),
7) Intra-Americas Seas Initiative(IASI), a multi-national effort to investigate the ocean dynamics in the Gulf of Mexico, Caribbean Sea and adjacent Atlantic ocean (present),
8) Interhemispheric and Intergyre Exchange Processes in the Upper Limb of the Meridional Overturning Circulation, a modeling effort at the University of Miami,
9) Bifurcation of the South Equatorial Current (BISEC), a joint US (URI, NOAA/AOML) and Brazil (University of Sao Paulo) effort to investigate the interbasin exchange of heat in the tropical Atlantic (proposed),
10) South Western Atlantic Circulation Experiment (SWACE), to investigate the controlling mechanisms driving the variability of the oceanic circulation in the southwestern Atlantic region (proposed).
11) Enhancement of the PIRATA array, a joint AOML/PMEL to deploy two moorings in the year 2000 (proposed).

Collaboration Efforts with Other Scientists and Institutions

NOAA/AOML scientists already work in close collaboration with researchers of other institutions in the NBC Ring Experiment and ACCE. Ilana Wainer and Edmo Campos, scientists at the University of Sao Paulo, will be working in close collaboration with Gustavo Goni and Molly Baringer in the analysis of the XBT data. Scientists at the University of Cape Town (C. Duncombe Rae) and at the South African Meteorological Service (Louis Vermaak) have already expressed their intentions in collaborating with this effort.

G. Goni (GG) is a Co-PI in the (NSF funded) NBC Ring Experiment, and is in close collaboration with the other PI's (B.Johns, P. Rhichardson, S. Garzoli, and D. Fratantoni). GG is also a collaborator in the BISEC proposal, to be submitted to NSF, and participates in a pilot project with colleagues at the NOAA/Hurricane Research Division, National Hurricane Center and University of Miami to develop a scheme to investigate the sudden intensification of hurricanes when they travel over warm mesoscale ocean features.

Collaboration is planned with NWP, modeling and assimilation groups under this and the related proposal (Yu and Weller) for producing global flux fields. Weller and Hosom will continue to interact with the Southampton Oceanographic Center (SOC) VOS and atmospheric-sea flux group (Taylor, Josey and Kent).

7 Summary

Mesoscale dynamics dominate the mass and heat transports across the equator and represents a key mechanism to drive SST changes is the region. Climate fluctuations known as the North Atlantic Oscillation (NAO) have been associated to the tropical Atlantic, where SST variability and associated changes in the winds, sea level pressure, and upper ocean dynamics, occur on interannual to decadal time scales. The flow of upper ocean waters across the equator, part of the Meridional Overturning Circulation (MOC), and heat fluxes dominate the equatorial and tropical meridional SST gradients in the tropical Atlantic.

Given the importance of the tropical Atlantic in climate variability and the scarcity of observations in the region, the COSTA workshop (COSTA Report, 1999) recommended improved measurments on key VOS routes to enhance the climate observing system in the region and:

- Maintain high density XBT lines in the North Brazil Current,
- Maintain high density XBT lines in the central Atlantic (25W),
- Conduct direct flux measurements from research vessels, and
- Monitor the sea surface salinity.

According to these recommendations, it is proposed here to maintain two VOS lines with high density XBT observations, surface salinity from thermosalinograph and meteorological observations from IMET instrumentation and provide direct observations to:

a) investigate the space-time evolution of the upper ocean thermal structure, b) investigate the upper ocean transport across the VOS lines, c) estimate the heat transport, d) investigate air-sea coupling.

The measurements obtained from this proposal will benefit the current observing system by providing information in key regions which are not currently being sampled. These measurements combined with remote sensing data and modeling efforts will greatly benefit climate studies in the tropical Atlantic by achieving what no other current or proposed observational methodology can achieve:

complement the current observing system to investigate long term spatial-temporal variability of mesoscale oceanic features and their impact on climate.

8 References

Baringer, M. O., and D. Mayer. On The Mean and Fluctuating Temperature Field along a section of the SubTropical North Atlantic Ocean. *J. Phys. Oceanogr.*, *submitted*, 1999.

Bitterman, D.S. Automated XBT Launcher for use on Ships of Opportunity. Presented at Ocean's 95 Conference, San Diego, Calif. October 9-12, 6 pp., 1995.

Bourles, B., R. L. Molinari, E. J. Johns, D. W. Wilson, and K. D. Leaman. Upper Layer Currents in the Western Tropical North Atlantic, *J. Geophys. Res.*, **104**, 1361-1375, 1999.

da Silva, A. M., C. C. Young and S. Levitus. Atlas of Surface Marine Data 1994, Volume 1: Algorithms and Procedures. NOAA Atlas NESDIS 7, 1995.

da Silva, A. M., C. C. Young and S. Levitus. Atlas of Surface Marine Data 1994. NOAA Atlas NESDIS 7, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Washington D.C., 1994.

Enfield, D. B., A. M. Mestas-Nunez, D. A. Mayer, and L. Cid-Serrano. How Ubiquitous is the Dipole Relationship in the Tropical Atlantic Sea Surface Temperatures ?, *J. Geophys. Res.*, **104**, 7841-7848, 1999.

Enfield, D. B., and D. A. Mayer. Tropical Atlantic SST variability and its relation to El NiM-qo-Southern Oscillation. *J. Geophys. Res.*, **102**, 929-945, 1999.

Enfield, D. B. and D. A. Mayer. Tropical Atlantic SST Variability and its Relation to El Nino-Southern Oscillation. *J. Geophys. Res.*, **102**, 929-945, 1997.

Folland, C. K. and D. E. Parker. Correction Of Instrumental Biases In Historical Sea-Surface Temperature Data. *Q. J. Roy. Met. Soc.*, 121(522), 319 - 367, 1995.

Fratantoni, D. M., W. E. Johns, and T. L. Townsend. Rings of the North Brazil Current: Their Structure and Behavior Inferred from Observations and a Numerical Simulation, *J. Geophys. Res.*, **100**, 10633-10654, 1995.

Garzoli, S. L., ed. COSTA. Climate Observing System for the Tropical Atlantic. Workshop Report, Miami, May 4-7, 1999.

Gilson, J., D. Roemmich, B. Cornuelle and L-L. Fu. The Relationship of TOPEX/Poseidon Altimetric Height to Steric Height and Circulation in the North Pacific, *J. Geophys. Res.*, 1999.

Goni, G. J. and W. Johns. Synoptic Study of North Brazil Current Rings from Altimetry. *In preparation*, 2000.

Goni, G. J., S. L. Garzoli, A. J. Roubicek, D. B. Olson and O. B. Brown. Agulhas Ring Dynamics from TOPEX/POSEIDON Satellite Altimeter Data. *J. Mar. Res*, **55**, 861-883, 1997.

Hansen D. V. and W. C. Thacker. Estimation of Salinity Profiles in the Upper Ocean. *J. Geophys. Res.*, **104**, 7921-7933, 1999.

Josey, S. A., E. C. Kent and P. K. Taylor. New insights into the Ocean Heat Budget Closure Problem from analysis of the SOC Air-Sea Flux Climatology, *Journal of Climate*(accepted), 1999.

Kaplan, A., M. A. Cane, Y. Kushmir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan. Analysis of Global Sea Surface Temperature 1856-1991. *J. Geophys. Res.*, **103**, 18567-18589, 1998.

Kelly, P. S., K. M. M. Lwiza, R. K. Cowen and G. J. Goni. Low- salinity Lenses at Barbados, West Indies: Their Origin, Frequency and Variability, *J. Geophys. Res.*, (in press) 2000.

Kent, E. C., P. K. Taylor, B. S. Truscott and J. A. Hopkins. The accuracy of Voluntary Observing Ship's Meteorological Observations, *J. Atmos. and Oceanic Tech.*, 10(4), 591 - 608, 1993a.

Kent, E. C., R. J. Tiddy and P. K. Taylor. Correction of marine daytime air temperature observations for radiation effects, *J. Atmos. and Oceanic Tech.*, 10(6), 900 - 906, 1993b.

Kent, E. C. and P. K. Taylor. A comparison of sensible and latent heat flux estimates for the North Atlantic ocean. *J. Phys. Oceanogr.*, 25(6), 1530 - 1549, 1995.

Kent, E. C. and P. K. Taylor. Accuracy of humidity measurements on ships: consideration of solar radiation effects. J. Atmos. and Oceanic Tech., 13(6), 1317 - 1321. Kent, E. C. and P. K. Taylor, 1997: Choice of a Beaufort Equivalent Scale, 1996.

Mayer, D. A., and R. H. Weisberg. A description of COADS surface meteorological fields and the implied Sverdrup transports for the Atlantic Ocean from 30S to 60N. *J. Phys. Oceanogr.*, **23**, 2201-2221, 1993.

Moyer, K. A. and R. A. Weller. Observations of surface forcing from the Subduction Experiment: A comparison with global model products and climatological data sets, *Journal of Climate*, **10**, 2725-2740, 1997.

Oberhuber, J. M. ; Roeckner, E. ; Christoph, M. ; Esch, M. ; Latif, M. Predicting the '1997 El Nio event with a global climate model *Geophys. Res. Lett.*, **25**, 2273-2276, 1998.

Roemmich, D., J. Gilson, B. Cornuelle, and R. Weller. The mean and time-varying meridional transport of heat at the tropical/subtropical boundary of the North Pacific Ocean, in preparation, 2000.

Rodwell, M. J., D. P. Powell, and C. K. Folland. Oceanic Forcing of the Wintertime North Atlantic Oscillation and European Climate. *Nature*, **398**, 320-323, 1999.

Servain, J., Wainer, I., A. Dessier and J. McCreary. Modes of Climate Variability in *Tropical Atlantic. Procedings of the International Association of Hydrologycal Sciences*, 1998.

Shay, L. K., G. J. Goni and P. Black. Effects of a Warm Oceanic Feature on Hurricane Opal, *Mon. Weath. Rev.*, **128**, 131-148, 2000.

Taylor, P. K., E. C. Kent, M. J. Yelland and B. I. Moat. The Accuracy of Wind Observations from Ships. Proc. Internat. COADS Winds Workshop, Kiel, Germany, 31 May - 2 June, 1994, Environmental Research Labs., National Oceanic and Atmospheric Administration, Boulder, Colorado, 132-155, 1995.

Taylor, P. K. and E. C. Kent. The Accuracy Of Meteorological Observations From Voluntary Observing Ships - Present Status And Future Requirements. First Session of the CMM Subgroup on Voluntary Observing Ships, Athens, 8 - 12 March, 1999., (to be published by WMO) 1999.

Taylor, P. K., E. F. Bradley, C. W. Fairall, D. Legler, J. Schulz, R. A. Weller, and G. H. White. Surface fluxes and surface reference sites, 1999.

Taylor, P. K., E. C. Kent, M. J. Yelland and B. I. Moat. The Accuracy Of Marine Surface Winds From Ships And Buoys. CLIMAR 99, WMO Workshop on Advances in Marine Climatology, Vancouver, 8 - 15 Sept. 1999, 1999a.

Watanabe, M. and M. Kimoto. Tropical/Extratropical Conection in the Atlantic Atmosphere/Ocean Variability. *Geophys. Res. Let.*, **26**, 2247-2250, 1999.

Weller, R. A. and S. P. Anderson. Surface Meteorology and air-sea fluxes in the western equatorial Pacific warm pool during the TOGA Coupled Ocean-Atmosphere Experiment. *J. Climate*, **9**, 1959-1990, 1996.

Woodruff, S.D., R.J. Slutz, R.L. Jenne, and P.M. Steurer. A comprehensive ocean-atmosphere data set. *Bull. Amer. Meteor. Soc.*, **68**, 1239-1250, 1987.

Yang, J. A Linkage between decadal Climate Variations in the Labrador Sea and the Tropical Atlantic Ocean. *Geophys. Res. Let*, **26**, 1023-1026, 1999.

Zebiak, S. E. Air-Sea Interaction in the Equatorial Atlantic Region, *Journal of Climate*, **6**, 1567-1586, 1993.

GUSTAVO J. GONI

B.S., Buenos Aires Institute of Technology, 1982 (oceanography)
M.S., The Pennsylvania State University, 1986 (acoustics)
Ph.D., University of Miami, 1991 (ocean engineering)
Post-Doc, University of Miami, 1992-1994
Senior Research Associate, University of Miami, 1994-1997
Oceanographer, Assistant Scientist, NOAA/AOML, 1997-present
Adjunct Faculty member, University of Miami, 1999-present

Single, U.S, Spanish and Argentine citizen.

Publications

Comparison of Hydrographic and Altimetric Estimates of Sea Level Height Variability in the Atlantic Ocean. Mayer, D. A., M. O. Baringer, R. L. Molinari and G. J. Goni. *Journal of Geophysical Research*, **submitted**, 1999.

Combining Altimeter Observations and Oceanographic Data for Ocean Circulation and Climate Studies. S. Garzoli and G. Goni. ICSOS Book, 2000.

Transport Estimates and Variability of the Kuroshio Extension Current from Satellite Altimeter and Inverted Echosounders Data. G. Goni. *J. Geophys. Res.*, (in press) 2000.

Low-salinity Lenses at Barbados, West Indies: Their Origin, Frequency and Variability. P. Kelly, K. Lwiza, R. Cowen and G. Goni. *J. Geophys. Res.*, (in press) 1999.

Three Agulhas Rings Observed During the Benguela Current Experiment. S. Garzoli, P. Richardson, C. Duncombe Rae, D. Fratantoni, G. Goni and A. Roubicek. *J. Geophys. Res.*, **104**, 20971-20985, 1999.

Shay, L. K., G. J. Goni and P. Black. Effects of a Warm Oceanic Feature on Hurricane Opal, *Mon. Weath. Rev.*, **128**, 131-148, 2000.

Agulhas Rings Dynamics from TOPEX/POSEIDON Satellite Altimeter Data. G. Goni, S. Garzoli, A. Roubicek, D. Olson and O. Brown. *J. Mar. Res.*, **55**, 861-883, 1997.

Monitoring the upper southeastern Atlantic transports using altimeter data. S. Garzoli, G. Goni, A. Mariano and D. Olson. *J. Mar. Res.*, **55**, 453-481, 1997.

Dynamics of the Brazil-Malvinas Confluence based on inverted echo sounders and altimetry. G. Goni, S. Kamholz, S. Garzoli and D. Olson. *J. Geophys. Res.*, **101**, 16273-16289, 1996.

Mesoscale Ocean Variability Signal from GEOSAT Altimeter Data in the SW Atlantic Ocean: A Comparison of Three Different Data Sets. G. Goni, G. Podesta, O. Brown and J. Brown. *Bolm. Inst. Oceanogr.*, Sao Paulo, **43**, 101-110, 1995.

Surface Mixed Layer and Temperature and Layer Depth in Waters off the Argentinian Coast. Novarini, J, S. Blanc and G. Goni. *J. Geophys. Res.*, **88**, 5987-5996, 1983.

MOLLY O. BARINGER

B.S., Tulane University, 1985 (mathematics)
Ph.D., MIT, Joint Program in Oceanography and Oceanographic Engineering, 1991 (Physical Oceanography)
Programmer/Analyst, Naval Oceanographic Research and Development Activity, NSTL Station, Miss, 1987-1987
Graduate Research Assistant, Woods Hole Oceanographic Institution, 1987-1993.
Oceanographer, Assistant Scientist, NOAA/AOML, 1994-1998
Oceanographer, Associate Scientist, NOAA/AOML, 1998-present

Publications

On The Mean and Fluctuating Temperature Field along a section of the SubTropical North Atlantic Ocean. Baringer, M. O., and D. Mayer. *J. Phys. Oceanogr., submitted*, 1999.

Comparison of Hydrographic and Altimetric Estimates of Sea Level Height Variability in the Atlantic Ocean. Mayer, D. A., M. O. Baringer, R. L. Molinari and G. J. Goni. *Journal of Geophysical Research, submitted*, 1999.

Atlantic Ocean baroclinic heat flux at 24 to 26° N. Baringer, M. O'Neil, and R. Molinari. *Geophysical Research Letters*, **26**, 3, 353-356, 1999.

A Review of the Physical Oceanography of the Mediterranean Outflow. Baringer, M. O'Neil and J. F. Price. *Marine Geology*, **155**, 1-2, 63-82, 1999.

Preliminary results from WHP sections I8N/I5E in the Central Indian Ocean. Talley, L. D. and M. O. Baringer. *Geophysical Research Letters*, **24**, 21, 2789-2792, 1997.

Deep Upwelling and Diffusivity in the Southern Central Indian Basin. McCarthy, M. C., Lynne D. Talley and Molly Baringer. *Geophysical Research Letters*, **24**, 21, 2801-2804, 1997.

Gordon, A. L., S. Ma, D. B. Olson, P. Hacker, A. Ffield, L. D. Talley, D. W. and M. Baringer. Advection and Diffusion of Indonesian Throughflow within the Indian Ocean South Equatorial Current, 1997. *Geophysical Research Letters*, **24**, 21, 2573-2576.

Mixing and spreading of the Mediterranean outflow. Baringer, M. O'Neil and J. F. Price. *JPO*, **27**, 8, 1654-1677, 1997.

Momentum and energy balance of the Mediterranean outflow. Baringer, M. O'Neil and J. F. Price. *JPO*, **27**, 8, 1678-1692, 1997.

Heat flux at 24° to 26° N revisited. Baringer, M. *The Atlantic Climate Change Program Proceedings from the principal investigators meeting May, 1996*, Anne-Marie Wilburn, ed, UCAR, Boulder Colorado, 1996.

ROBERT A. WELLER

B.A., Harvard University, 1972 (engineering and applied physics)
Ph.D., Scripps Institution of Oceanography, University of California, San Diego, 1978
Research Assistant, Division of Engineering and Applied Physics, 1970-1972
Research Assistant, Scripps Institution of Oceanography, University of California, 1972-1978.
Postgraduate Research Oceanographer, Scripps Institution of Oceanography, University of California, 1978-1979
Postdoctoral Scholar, Woods Hole Oceanographic Institution, 1979-1980.
Postdoctoral Investigator, Woods Hole Oceanographic Institution, 1980
Assistant Scientist, Woods Hole Oceanographic Institution, 1980-1984
Associate Scientist, Woods Hole Oceanographic Institution, 1984-1992
Senior Scientist, Woods Hole Oceanographic Institution, 1992-present
Tenure awarded, Woods Hole Oceanographic Institution, 1988
Henry Bryant Bigelow Chair for Excellence in Oceanography, WHOI, 1993-present.

Publications

Diurnal Cycling: Observations and Models of the Upper Ocean Response to Diurnal Heating, Cooling, and Wind-mixing. Price, J. F., R. A. Weller, and R. Pinkel. *J. Geophys. Res.*, **91**, 8411-8427, 1986.

Forced Ocean Response During the Frontal Air-sea Interaction Experiment, Weller, R. A., D. L. Rudnik, C. C. Eriksen, K. L. Polzin, N. S. Oakey, J. M. Toole, R. W. Schmitt, and R. T. Pollard. *J. Geophys. Res.*, **96**, 8611-8638, 1991.

Meteorological Variability and Air-sea Fluxes at a Closely Spaced Array of Surface Moorings. Weller, R. A., D. L. Rudnik, and N. J. Brink. *J. Geophys. Res.*, **100**, 4867-4883, 1995.

Surface Meteorology and Air-sea Fluxes in the Western Equatorial Pacific Warm Pool During the TOGA Coupled Ocean-Atmosphere Response Experiment. Weller, R. A., and S. P. Anderson. *J. Climate*, **9**, 1959-1990, 1996.

Observations of the Vertical Structure of the Oceanic Boundary Layer. Weller, R. A., and A. J. Plueddemann. *J. Geophys. Res.*, **101**, 8789-8806, 1996.

Surface Buoyancy Forcing and the Mixed Layer of the Western Pacific Warm Pool: Observations and 1-D Model Results. Anderson, S. P., R. A. Weller, and R. B. Lukas. *J. Climate*, **9**, 3056-3085, 1996.

Arabian Sea Surface Winds and Ocean Transports determined from ERS-1 Scatterometer. Halpern, D., M. H. Freilich, and R. A. Weller. *J. Geophys. Res.*, **103**, 7799-7805, 1998.

Pacific Warm Pool Sea Surface Temperature Regulation During TOGA COARE: Upper Ocean Feedback. Lagerloef, G. S. E., R. Lukas, R. A. Weller, and S. P. Anderson. *J. Climate*, 1998.

A One-year Record of Atmospheric Forcing From the Arabian Sea. Weller, R. A., M. B. Baumgartner, S. A. Josey, A. S. Fisher, and J. C. Kindle. *Deep-Sea Res.*, 1998.

The Coupled Ocean Atmosphere Response Experiment (COARE): An Interim Report. Godfrey, J. S., R. A. Houze, R. H. Johnson, R. Lukas, J. L. Redelsperger, A. Sumi, and R. Weller. *J. Geophys. Res.*, 1998.

DAVID S. HOSOM

M.S., Long Island University (Marine Science), 1971
M.S.E.E., Polytechnic Institute of Brooklyn, 1963
Design Engineering, Crosley Division of Avco, Cincinnati, 1958-1959
Design Engineering, Sperry Gyroscope Company, Lake Success, 1959-1961
Design Engineering, Airborne Instrument Department, Deer Park, 1961-1963
Assistant Program Manager, Ocean System Dept, Grumman Aerospace Corporation, New York, 1963-1971
Research Associate, Dept Ocean Engineering, WHOI, 1971-1979
Chief Engineering, Benthos Inc, North Falmouth, 1979-1985
Research Specialist, Dept Physical Oceanography, WHOI, 1985-1988
Senior Engineering, Dept Physical Oceanography, WHOI, 1988-present

Publications

ALVIN 120VDC/28VDC Electrical Systems. Hosom, D. S., N. C. Forrester, and B. B. Walden. *Proceedings of the Marine Tech Soc*, 1986.

Improved Meteorological Measurements from Ships and Buoys. Prada, K., D. Hosom, and A. Hinton. *Proceedings of the Marine Tech Soc*, 1990.

Improved Meteorological Measurements from Buoys and Ships for the World Ocean Circulation Experiment. *Proceedings of the Marine Tech Soc*, 1989.

An Intelligent Chilled Mirror Humidity Instrument, D10IQ. Hosom, D. S., G. H. Crescenti, C. L. Winget, J. F. Price, S. Weisman, and D. P. Doucet. *J. Atmos. Ocean Tech*, **8**, 585-596.

The IMET (Improved Meteorology) Ship and Buoy Systems. Hosom, D. S., R. A. Weller, R. E. Payne, and K. E. Prada. *J. Atmos. Ocean Tech*, **12**, 527-540, 1995.

High Quality Surface Temperatures for Volunteer Observing Ship. Allsup, G. and D. S. Hosom. *IEEE 96 Oceans Conference*, 1274-1278, 1996.

Air-Sea Interaction Observations from Buoys and VOS. Hosom, D. S. *Oceans 98*, 1998.

Upgraded Vector Measuring Current Meter. Hosom, D. S., R. A. Weller, G. Allsup, S. Anderson, and R. Trask. *Oceans 99*, 1999.